A Quantified Comparison of Commercial CF-LMPAEK Tapes

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ABSTRACT

Many commercial grades of CF-LMPAEK prepreg are available in the current market, with new versions constantly being developed to respond to new needs in the field of high-throughput manufacturing for aerospace applications. However, the information supplied by the manufacturer of a given prepreg may include assumptions, oversights, or even errors, with the degree of these uncertainties compounding and making the continuity and comparability of two CF-LMPAEK prepregs from two different sources dubious at best. In this work, a total of six versions of CF-LMPAEK are investigated using continuous and localised measurement techniques, using large databases to draw conclusions around critical material properties such as width, thickness, and fibre mass content. It is found that almost all available prepregs yield a median width value above the target, with the 95% confidence interval of the respective prepregs having little to no overlap with one another, thus limiting interchangeability. The thickness and fibre mass content are also far from consistent amongst prepregs, increasing the number of uncertainties when attempting to transfer experience acquired with a given product to a new one.

1. Introduction

The push towards ever higher production rates in aerospace shows no signs of slowing down. A recent market assessments by Airbus alone predicted a total demand of 42,450 aircraft between 2025 and 2044[1], equating to an average of 228 aircraft per month. To achieve such a high production rate, rapid manufacturing and assembly processes are essential, particularly those which leverage a high degree of automation. Among the most sought-after processes which fill these criteria are thermoplastic welding and thermoplastic Automated Fibre Placement (AFP), both of which have the capacity to forego material and time-intensive processes such as drilling, riveting, vacuum-bagging, and autoclave consolidation, all of which are integral in the current manufacturing and assembly architecture of modern composite aircraft. While both processes have made significant advances in their performance, repeatability, and industrialisation, they have had to do so upon a very dynamic landscape. In order to achieve a high Technology Readiness Level (TRL), aircraft components and systems leveraging these technologies must have an extremely stable base, consistently obtaining the same performance properties in a series production setting. Such a task is made extremely difficult by distinct variations in the material supply.

The topic of prepreg quality was discussed regularly in the early 2000s[7, 6], with material only considered suitable for automated processes such as AFP if it maintained uniform thickness, tight width tolerances, and few to no voids[7]. While the general quality of prepregs can be considered higher now than it was at the time of those studies, the challenge of prepreg quality continues to persist. In the current market, consecutive batches of a given composite prepreg are known to vary from one another, from the fibre distribution, thickness consistency, and width consistency, among others. Furthermore, programmatic changes often promote investigations into variants of a given prepreg, often from competing commercial suppliers, in order to decrease the robustness of the aircraft supply chain and reduce the risk of single dependencies. While advantageous from an economic point of view, such a change inherently requires a regression back to very low TRL phases, incurring further costs and delays if the competing material grades differ significantly from one another.
This work aims to shed light on this challenge by investigating a single thermoplastic prepreg, CF-LMPAEK, from several commercial suppliers to quantify their differences in critical areas affecting thermoplastic manufacturing, particularly AFP.

2. Methodology

Commercially available as of the late 2010s [5], LMPAEK is a polymer designed to meet the requirements of the modern aerospace industry. LMPAEK aims to provide similar mechanical properties to already qualified high-performance polymers (PEEK, PPS) while also targeting higher production speeds. Carbon fibre-reinforced LMPAEK (CF-LMPAEK) has been investigated extensively since its release, with various demonstrators produced to showcase its potential. These include large-surface, load-bearing components as shown in Figure 1.

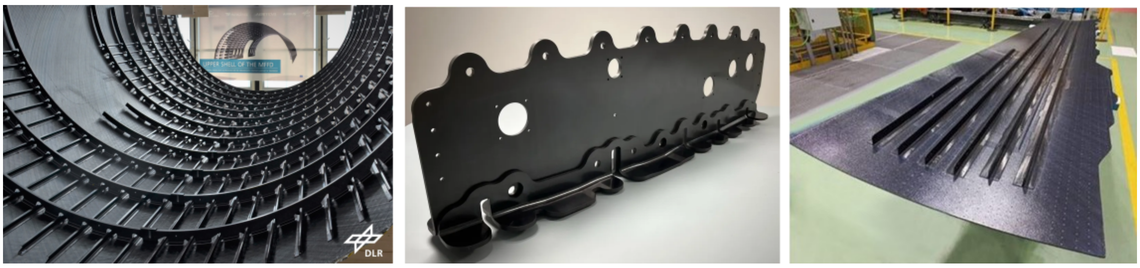

Figure 1: Recent aerospace demonstrators manufactured using CF-LMPAEK: DLR's MFFD (left)[3], Daher's highly-loaded wing rib (centre)[2], and FIDAMC's stiffende morphing wing skin (right)[4]

While originally there was only a single supplier of CF-LMPAEK prepreg (Toray, then TenCate with Toray Cetex® TC1225), today both large and small prepreg producers offer CF-LMPAEK products of varying widths, thicknesses, and fibre concentrations. While LMPAEK in its pure polymer form continues to come from a single source (Victrex under the designation AE™250), different producers use different means to produce their final products. These range from traceable decisions, such as the choice of continuous carbon

fibre or width control method (slitting or pultrusion), to decisions obscured behind confidentiality, particularly as concerns the use of solvents or the means with which quality assurance is performed.
The goal of this work is to quantify the differences between several grades (commercial and experimental) of CF-LMPAEK to provide insight into, among other things, how well knowledge gained with one grade can be transferred to another. The accuracy of post-procurement measurements to datasheet values will also be summarised.

2.1. Materials

This study investigated a total of six grades of CF-LMPAEK. In the interest of anonymity, the suppliers of the prepregs are not provided explicitly. Table 1 lists the materials investigated as well as their respective properties. All tapes are specified in their respective datasheets to have a fibre mass content (FMC) between 60 and 66%. Both 12.70 mm (1/2”) and 6.35 mm (1/4”) have been included in this work as almost all AFP facilities utilise one or both of these standard widths. The choice was also made to include prepregs still in the development phase and compare them to commercially “stable” counterparts. As will be discussed, this study employed both continuous and localised measurement techniques. As a result, the material spool length is stated.

Table 1: Compared grades of commercial CF-LMPAEK

Designation	Target width [mm]	Target FMC [%]	Spool length [m]	Product maturity
1/2”-01	12,70	66	183	Commercial
1/2”-02	12,70	63	500	Commercial
1/2”-03	12,70	66	500	Commercial
1/2”-04	12,70	60	286	Development
1/4”-01	6,35	62	225	Commercial
1/4”-02	6,35	66	152	Development

2.2. Measurement Systems

AFP employs hundreds if not thousands of metres of prepreg to manufacture laminar parts, resulting in a high sensitivity to localised properties along the full length of the material spool.

Continuous Measurement

A novel feature of this work is the measurement of material properties in a continuous fashion, ie along the entire length of the material spool. This was achieved using the Textechno (Herbert Stein GmbH & Co. KG Textile Mess- und Prüftechnik) TAPETEST facility [10], pictured in Figure 2.

Figure 2: TAPETEST facility [10]

This facility measures almost the entire length of a given prepreg spool (bar the length required for positioning and tensioning) with millimetre resolution. Due to the sheer quantity of data generated, corresponding datapoints are generated at intervals of 100 mm, resulting in thousand of entries and enabling detailed analysis of the tape quality. Among other properties, the TAPETEST facility measures the width, thickness, and surface roughness of the prepreg, all of which have a distinct impact on the consolidation quality of AFP-manufactured parts. These properties are obtained by visual (laser-based) scanning methods integrated in the TAPETEST equipment and processed using proprietary Textechno software. The non-destructive nature of this facility makes it highly valuable, as data obtained can be directly applied to the manufacturing environment.

Local Measurement

While continuous non-destructive testing provides a great deal of information on the prepreg, traditional destructive testing still has its place of providing detailed, albeit localised, information, particularly regarding the composition and homogeneity of the material. In this work, localised destructive testing in the form of digital microscopy and acid digestion was used to obtain information on FMC and the thickness variation of the various prepreg materials.
Optical microscopy was performed using a Keyence VR-5000 3D digital system, with magnifications of 500 or 1000 used to produce micrograph images. Assessments of the prepreg thickness and fibre content were performed using a previously published image analysis software developed by DLR [9, 8]. While the datasets of the continuous method were understandably larger than those of the local measurements, microscopy in particular used over 20 samples per material to generate a statistically-relevant database. Previous investigations have found that while the automated analysis software provides great insight into the prepreg composition, it is extremely sensitive to artefacts in the micrograph images. One particular area of concern is that certain fibre types seem to be more brittle than others, presenting uneven surfaces which the software can misinterpret. While other solutions are currently being explored, acid digestion was used in the meantime to correct for this shortcoming and provide the central value through which distribution data was scaled. Acid digestion was performed in accordance to DIN EN 2564 with sample

masses between 1.0 and 1.4 g.

3. Results

While many prepreg properties are relevant for AFP manufacturing, this work focuses on the prepreg width (important for layup planning and hence the prevention of parallel gaps/overlaps in a given ply), prepreg thickness (related to the ply count for a given laminate thickness and) and thickness stability (a potential source of interlaminar porosity and laminate waviness), and prepreg fibre distribution (important for strength/stiffness properties, homogeneous stress distribution, and homogeneous heating when using laser-based heat sources).

Prepreg Width

Figure 3 shows the prepreg widths as measured by the TAPETEST system for both 12.70 mm and 6.35 mm configurations. As can be seen, the 12.70 mm prepregs each exhibited a distinctive width with minimal overlap between individual products.

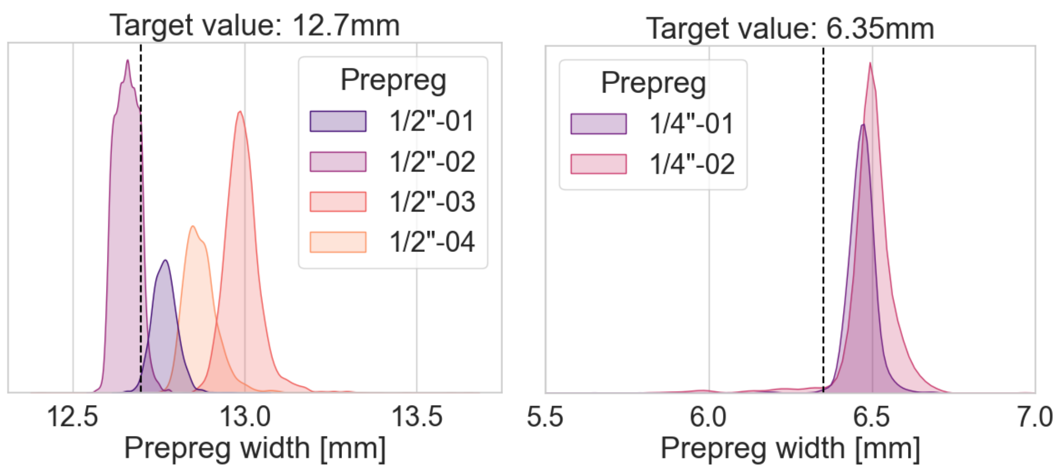

Figure 3: TAPETEST-measured prepreg width for 12.70 mm (left) and 6.35 mm (right) materials

Prepregs 1/2”-01 and 1/2”-02 were closest to the target values, with offsets of -0.04 mm and +0.07 mm, respectively. This does implies that with all other parameters being equal, switching between these two prepregs requires consideration of a 0.11 mm offset. Prepregs 1/2”-03 and 1/2”-04 were significantly further from the desired value; 0.29 mm and 0.17 mm, respectively. In the case of Prepregs 1/2”-03, it is possible that miscommunication in the manufacturing caused targeting of a metric width (13 mm) rather than imperial. However, order and delivery documentation confirm the target width of 12.70 mm, meaning that this prepreg was a significant distance from its target value. It is interesting to note that of the four 12.70 mm prepregs, 1/2”-01, 1/2”-03, and 1/2”-04 were all cut to their final widths using slitting, while 1/2”-02 was produced directly as 12.70 mm material. This goes some way to clarify why 1/2”-02 was the only prepreg below the target value. Prepregs 1/4”-01 and 1/4”-02 were significantly closer to one another, with only a 0.03 mm separation. As a result, switching between these tapes would cause minimal disruption to an established manufacturing chain, assuming of course that all other prepreg properties were equivalent. It should also be emphasised that while these two prepregs exhibited a similar width to one another, they were both reasonably removed from the target width of 6.35 mm, which would of course affect the ply planning of a laminar part.

Prepreg Thickness and Thickness Stability

Figure 4 shows the TAPETEST-measured thickness of prepregs. Using this system, two major observations could be made. Firstly, while prepregs in this study typically exhibit a higher than average Fibre Areal Weight (FAW >145gm^2), Prepreg 1/2”-04 was manufactured to have a significantly lower FAW. As a result, the closeness of the median thickness values to one another may reveal an area for improvement for TAPETEST in its current configuration. Secondly, the spread of measured thicknesses is quite high using this method, with measurements varying by up to 50% of the nominal central value. The significance of this spread is highlighted in Figure 5, where the magnitude of variation in the thickness dominates that of the width, making the effective prepreg cross-section largely dependent on thickness. However, as thickness can be dominated by micro rather than macro properties of the tape, these thickness measurements were compared to those based on optical microscopy.

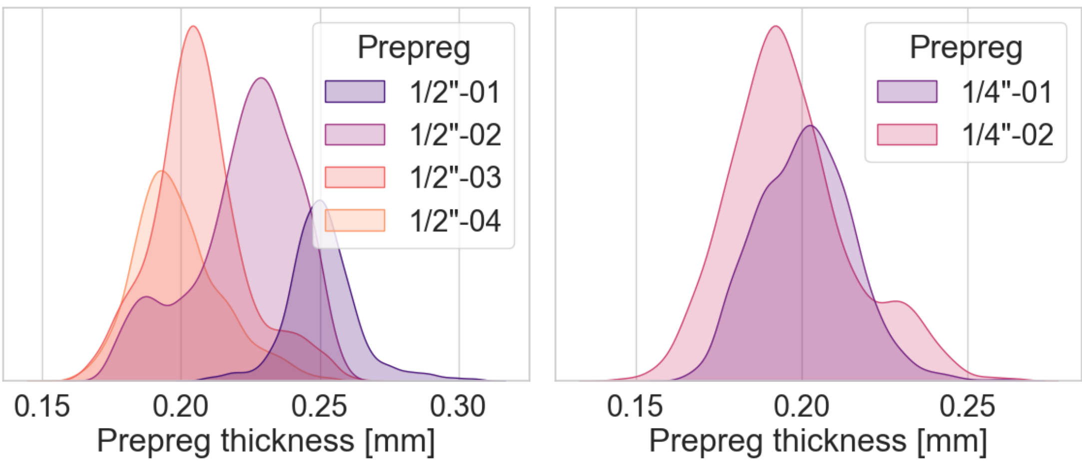

Figure 4: TAPETEST-measured prepreg thickness for 12.70 mm (left) and 6.35 mm (right) materials

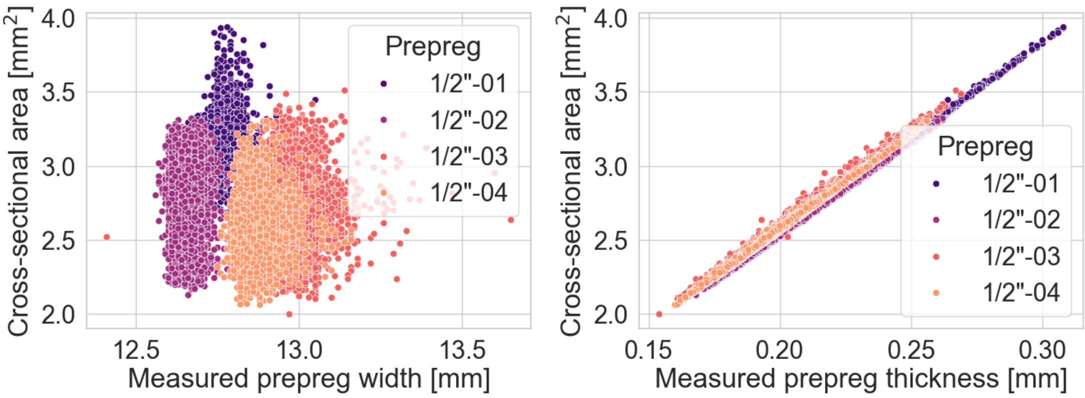

Figure 5: Dependency of the calculated prepreg effective cross-section with respect to the prepreg width (left) and thickness (right)

Figure 6 shows the thickness of prepregs 1/2"-01, 1/2"-03, and 1/2"-04 as determined by micrographs. As can be seen, these results are significantly different to those of Figure 4.

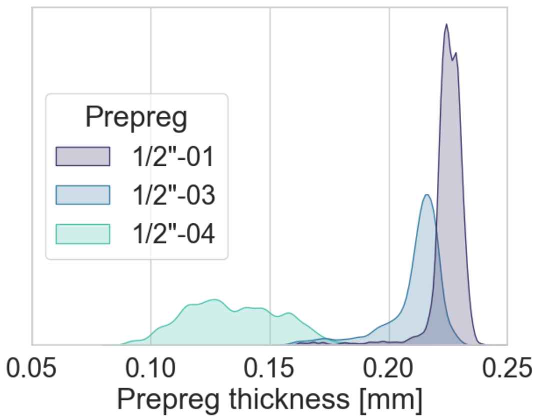

Figure 6: Microscopy-measured thickness of selected 12.70 mm prepregs

The spreads of prepregs 1/2"-01 and 1/2"-03 were much narrower using this method, with prominent nominal measured thicknesses of 0.23 mm and 0.21 mm, respectively. These values are closer to those otherwise expected and stated in the prepreg datasheets. The largest dissimilarity to Figure 4 was observed for prepreg 1/2"-04, which exhibited a lower nominal value of 0.13 mm, also closer to the expected datasheet value. Prepreg 1/2"-04 displayed the largest scattering of thickness values, spread evenly above and below the median value. Prepregs 1/2"-01 and 1/2"-03, on the other hand, exhibited strongly represented nominal thicknesses with scattering below this value, correlating to infrequent but still measurable reductions in the prepreg thickness. Examples of these local thickness reductions are shown in Figure 7. It should be noted that prepreg 1/2"-04 is still in the development phase and hence a less refined state is to be expected compared to commercially available products. However, this is nonetheless useful information informing how much variation may be expected for new and prototype materials such as this.

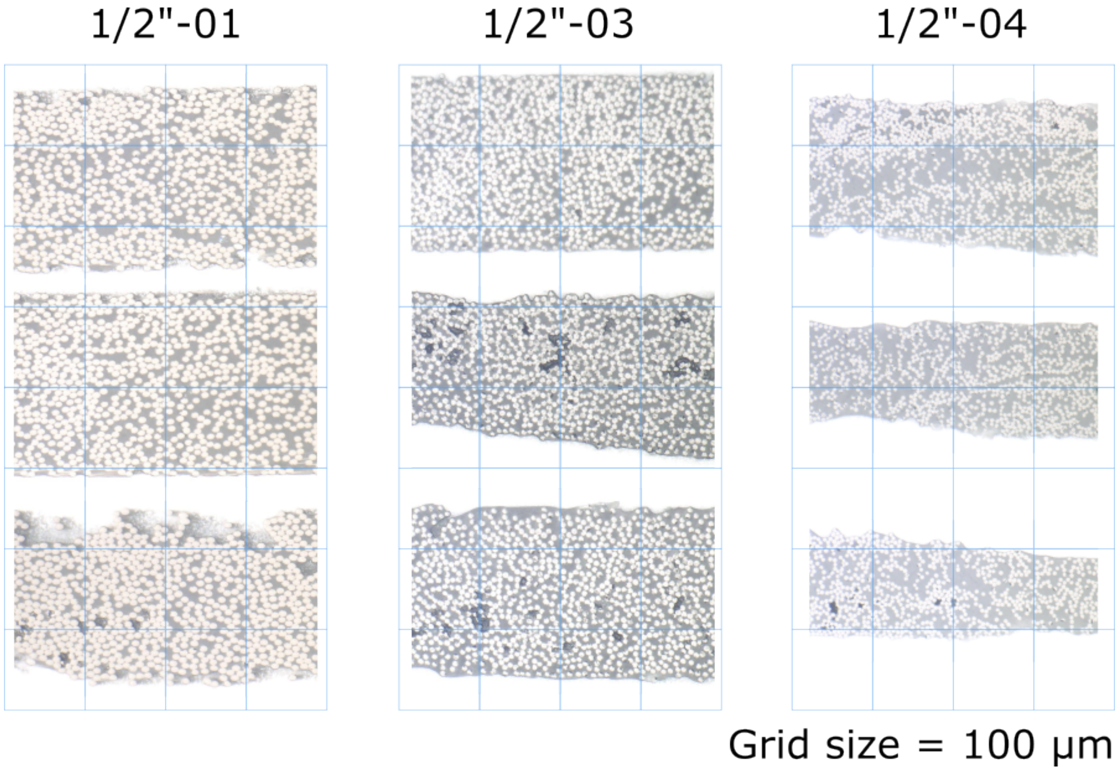

Figure 7: Microscopic composition of selected 12.70 mm prepregs

Comparing the continuous (laser) and local (micrograph) methods, it would appear that microscopy, though labour intensive, provides a more reliable assessment of prepreg thickness at this point in time. It should however be noted that the TAPETEST laser measurement method can always be improved to provide more accurate measurements in the future.

Prepreg Fibre Distribution

The prepreg fibre distribution as measured by microscopy is shown in Figure 8. As can be seen and as stated previously in Table 1, some of the prepreg had slightly different targets for the FMC. Prepregs 1/2"-01 and 1/2"-03 targeted 66% while 1/2"-04 targeted 60%. Interestingly, while the median values of the prepreg samples were close to their intended targets, each displayed a somewhat unique behaviour. The most prominent FMC value for prepreg 1/2"-01 was slightly higher that the intended target at 67.74%. However, this material exhibited a moderately bimodal distribution, implying areas of slightly higher and slightly lower fibre concentration within the prepreg. This is supported by the images in Figure 7. Prepreg 1/2"-03 exhibited a median FMC extremely close to its intended target, with less than 0.5% variation. It also displayed a multimodal distribution, though with a reduced degree of severity compared to the other materials. Finally, the development-grade prepreg 1/2"-04 had its collective distribution centred about its intended target, though it also exhibited a strong bimodal distribution with peaks at approximately 55% and 63%.

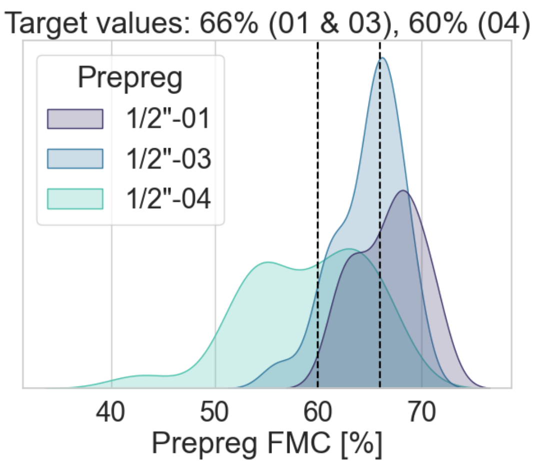

Figure 8: Microscopy-measured fibre mass content of selected 12.70 mm prepregs

Overall the analysis of these micrographs yielded useful insight into how varied the FMC of prepreg materials truly are.

4. Discussion

Figures 9 and 10 display the 95% confidence internals of prepreg width, thickness, and FMC for the materials investigated within this study.

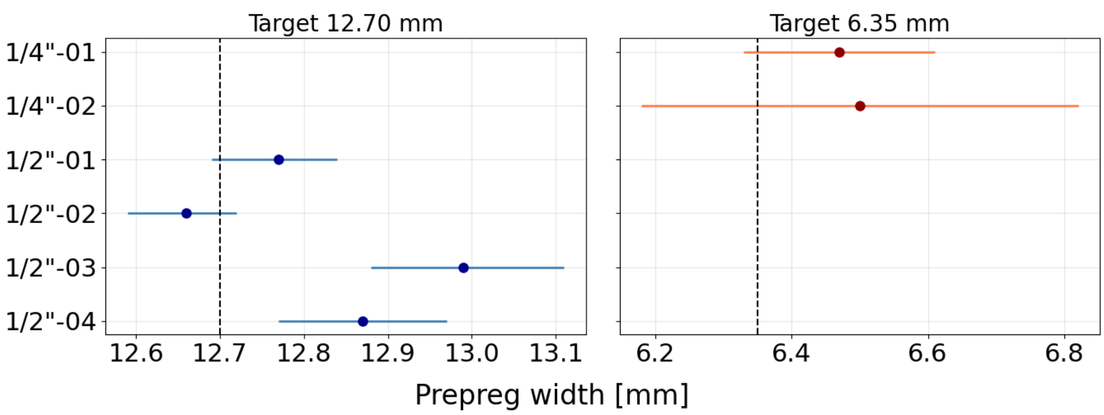

Figure 9: Comparisons of the measured prepreg widths - 95% confidence interval

These results of this work show that the median prepreg width varies significantly between the different grades of CF-LMPAEK, particularly for 12.70 mm versions. The confidence intervals of some prepregs overlap minimally with one another and some not at all, meaning at the very least that datasheet values of a given product may not be assumed inherently accurate. It should be noted that the spread of width values was itself rather minor - less than 1% for all 12.70 mm prepregs. This would imply that the problem is a systematic one and could be amended with alterations to the respective width-control facilities. As previously mentioned, the only prepreg product which exhibited a median width below the target threshold was produced using a process which did not include tape slitting. 6.35 mm prepregs exhibited similar median widths (both above the nominal value but close to one another), though the spread of measured width value was greater than the 12.70 mm prepregs; 2.2% and 4.9% for 1/4"-01 and 1/4"-02, respectively.

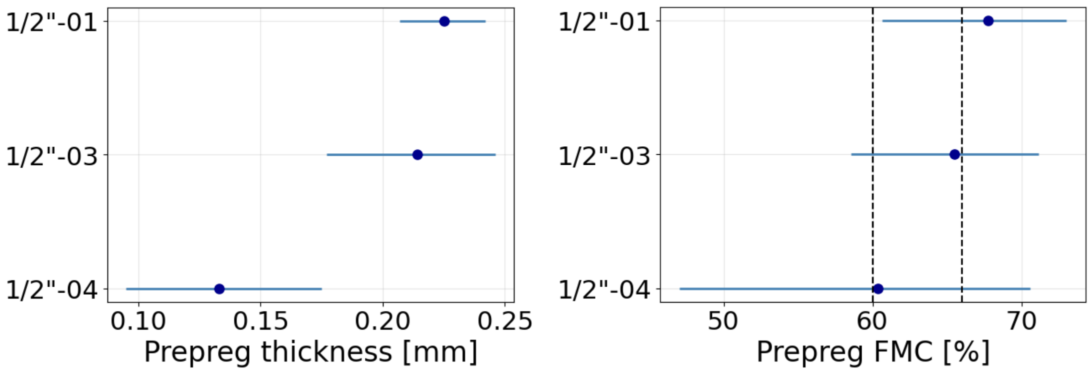

Figure 10: Comparisons of the measured prepreg thicknesses (left) and FMC (right) - 95% confidence interval

The thickness and averaged FMC of CF-LMPAEK prepregs investigated within this work seem at first glance of little interest/concern until the relevance of their units and scale are considered. For the case of thickness, the two materials with a similar FAW (1/2"-01 and 1/2"-03) agreed reasonable well with one another and their respective producer-supplied nominal values. However, the scale of deviations result in prepreg thickness variations of ± 15% for 1/2"-01 and ± 30% for 1/2"-02. This is clearly much greater than variations in the width and can have equally important repercussions on the final quality of the laminate, particularly as pertains to pores as delaminations or waviness in the fibre transverse direction. The homogeneity of fibres in the prepregs also yielded noteworthy observations. While a perfect fibre distribution is possible or expected, it is worth noting that the concentration of fibres can vary locally in the material by up to 10% from the target value. Such observations assist part design and analysis in an industry where a more precise placement of material (in comparison to hand-layup techniques) and local variations in material composition can compound to produce uncertainties in the bulk material properties. This technique can also assist in the development of new materials such as 1/2"-04, informing precisely where the fibre distribution needs to improve to achieve its desired final value.

5. Conclusion

This work investigated quantifiable differences between comparable, and in some instances directly "equivalent" CF-LMPAEK prepregs commercially available today. Using a combination and continuous and localised measurement techniques, it was shown that manufacturer-provided information did not always accurately reflect the true tolerances of the product. Median prepreg thickness were above the target value for almost all materials investigated, with only one 12.70 mm prepreg exhibiting a median width lower than the intended. Widths were generally tightly controlled (more so for 12.70 mm prepregs than 6.35 mm), remaining within 1% of the median value. However, the variation of median values between the respective materials means that substituting one for the other is not possible without detailed consideration of the consolidated prepreg width. This interpretation is supported by further observations of the prepreg thickness. While prepregs of comparable fibre areal weights exhibited comparable median thickness value, assessments of a large number of microscopic images that the deviation from this value can easily vary by a factor of two between tapes. These uncertainties in width and thickness make matching the consolidated material cross-section of two different prepregs challenging and may incur significant time and costs to find an adequate solution. Further analyses of the microscopic structure revealed that the fibre content can display a distinctly bimodal or multimodal distribution, particularly for prepregs still in their development phase. Understanding the prominent effective FMC of a given material allows a better accounting for mechanical and other properties following manufacturing.

6. Acknowledgements

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7. References

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